Mechanics of Granular Materials

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Unlike materials such as metals, polymers, concrete, rocks, etc., which derive their strength and deformation characteristics mainly from strong cohesive forces of chemical cementation, the constitutive relations of uncemented granular materials, eg. strength, modulus behavior, dilatancy, localization of deformations, shear band formation and instability behavior are, to a large extent, derived from interparticle friction resulting from normal forces acting on particles and particle groups.

Particle bonding by weak electrostatic and short- or long-term Coulomb forces may also influence, to a small extent, the constitutive behavior of granular materials. However, their behavior is mainly governed by interparticle friction which, in turn, under very low effective stress levels is highly dependent on gravitational body forces. Erosional processes, which among other effects, cause an irreversible loss of a very significant amount of fertile soil in the midwestern United States; dust storms and off-road locomotion are illustrative examples.

The force-deformation behavior of granular materials is fabric or internal structure dependent, highly nonlinear, dilatant and nonconservative. The gravity-induced stresses in laboratory specimens on Earth are nearly of the same order of magnitude as the externally applied tractions, thus limiting the size of the specimens. On the other hand, the same laboratory specimens must be sufficiently large to replicate the behavior of large geologic deposits in-situ, or the behavior of large masses of industrial or agricultural products during storage, handling and transportation.

During critical, unstable states, such as the liquefaction of saturated loose sands under earthquake or wave loading, landslides due to pore water pressure buildup, or the collapse of sensitive clays, gravity acts as a "follower load," causing these events to take place essentially instantaneously and making the sequence of such phenomena impossible to observe and study as they occur on Earth, either in the laboratory or in the field.

In granular materials, gravity-driven particle convection induces material inhomogeneities and anisotropies during testing, especially under low-confining pressures, which alters the initial fabric of the test specimens and hence their constitutive relations. Accordingly, from an engineering point of view, uncertainties of unknown magnitude are introduced into the laboratory tests performed to emulate the actual field behavior of large masses.

Under moderate to high stress levels, the influence of gravity on the behavior of test specimens may not be pronounced and, therefore, the test results in a terrestrial (1-g) environment may be sufficiently conclusive for engineering purposes. However, testing of granular materials under very low stress levels can only be performed in a microgravity environment in order to yield meaningful results. It should be emphasized again that the the laboratory specimen which would, on one hand, best resemble a magnified version of the elemental cube in a continuum mechanics sense, should, on the other hand, be representative, in a statistical sense, of the particle fabric of the real mass.

The gravity induced stresses within a specimen transform the experimental setup into a very complex boundary value problem, in which the constitutive properties and stability issues cannot be resolved by inverse identification techniques due to the highly nonlinear nature of the constitutive behavior. For the same reasons, one cannot determine the constitutive relations of granular materials at very low effective stress levels by extrapolating results from centrifuge tests performed at very high stress levels.

Because of the above considerations, NASA has supported the development of a microgravity experiment called mechanics of granular materials (MGM), figure 138. This experiment entails the performance of a test series of nine displacement-controlled triaxial compression tests on right cylindrical specimens 75 mm in diameter by 150-mm long, consisting of Ottawa F–75 banding sand, a natural quartz sand (silicon dioxide). Because Ottawa sand is widely used as a standard material in soil mechanics experiments on Earth, results from tests on the same material in a microgravity environment will allow direct comparisons with experimental results already obtained on Earth.
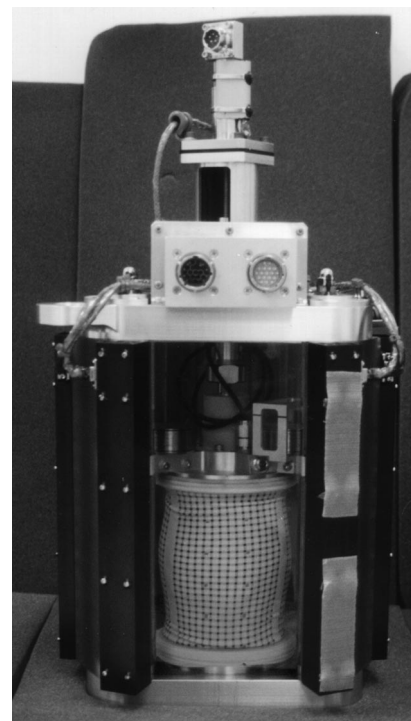
FIGURE 138.—Mechanics of granular materials test cell.

The sand has been tumbled, degreased, washed, and dried. It has been screened to

sizes of 0.1 to 0.3 mm (with no grains below 0.074 mm present—the demarcation size between coarse and fine granular materials), removing all silt and clay-sized particles. The soil specimens are contained in a latex sheath that is 0.3-mm thick and inprinted with a grid pattern so cameras can record relative changes in shape and position. On the top and bottom of each specimen are placed special platens. These are made of polished tungsten carbide steel to provide the necessary hardness and low coeffient of friction between the platens and the soil specimen.

Each specimen is placed in a test cell shaped like an equilateral prism consisting of a Lexan jacket sandwiched between metal end plates connected by guide rods. Within the Lexan jacket the cell is filled with water which is pressurized to keep the specimen stable under confinement during launch, and during re-entry in its postfailure configuration. An electric stepper motor on top of the test cell drives a gear assembly that moves the top platen, which is centered over the soil specimen by the guide rods along the longitudinal direction of the specimen. A load cell measures the resistance to deformation of the specimen during the prescribed displacement of the top platen.

Three fluid lines connect the test cell to the MGM hydraulic system. During the first mission the specimen is completely dry. One line is connected to the specimen and allows the air to escape from the specimen as it compresses. The second line supplies water to the jacket to confine the specimen and the third line measures the jacket water pressure. During the other missions, the specimens are completely saturated and the water is not allowed to escape from the specimen as it compresses. In other words, the tests are undrained tests. In this configuration, the air line is replaced by a water line. The fluid pressure on the test cells is enacted and controlled by two hydraulic accumulators which also measure pressure.
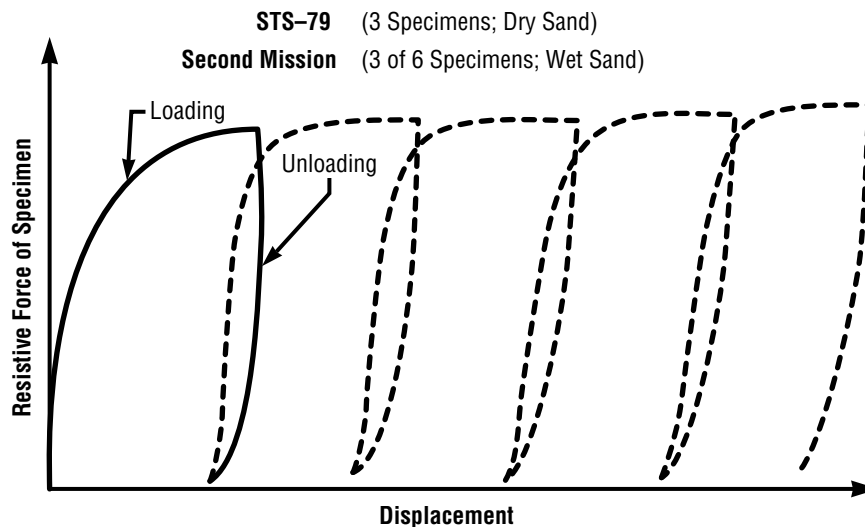

STS–79   (3 Specimens; Dry Sand)
Second Mission   (3 of 6 Specimens; Wet Sand)

FIGURE 139.—Typical compression-unloading sequence.

During each test, the test cell is held on a rigid test/observation pad mounted between an array of three CCD cameras and banks of small light-emitting diodes. Each camera is pointed at a different side of the prismatic Lexan jacket to provide full coverage of the specimen. The MGM video control system electronically obtains the images and transmits the signals to a portable video recorder. The stepper motor, accumulators, and cameras are controlled by the payload general support computer (PGSC), a laptop computer operated by the flight crew during the mission.

The first series of MGM tests, consisting of three dry specimens tested under drained conditions were performed during the STS–79 Shuttle–Mir mission, aboard the Space Shuttle Atlantis in September 1996. All tests were performed successfully, each under a different confining pressure, e.g. the first test was performed under a confining pressure of 0.007 lb/in^2; the second under 0.075 lb/in^2 and the third test under a confining pressure of 0.189 lb/in^2. All specimens were subjected to 5 compression-unloading cycles (fig. 139), resulting in a 25-percent longitudinal strain. Upon the completion of each test, the confining pressure was increased to 13 lb/in^2 to keep the deformed specimen stable and the test

cell was stowed according to procedures. Figure 140 was taken on Atlantis showing Mission Specialist Carl Walz observing an MGM specimen during testing.

Upon the completion of Shuttle mission STS–79, and the return of the Atlantis to Earth, the three MGM test cells were unstowed and flown to MSFC. There they underwent profilometer measurements at the MSFC Space Sciences Laboratory, using an MTI CCD 72, black and white detector, connected to a "frame grabber." Longitudinal profiles were obtained from the specimens at 5-degree rotation intervals. During the same time, holograms were also obtained using a HeNe-6328 A laser. To perform these activities, the specimens had to be removed from their test cells and be subjected to the same confining pressure of 13 lb/in^2 by drawing the air from the interconnected pores of their interior through a vacuum pump. The specimens are now kept at the MSFC MGM Laboratory and are scheduled to be flown to the University of Colorado, Boulder, for epoxy impregnation and thin sectioning to observe and analyze their interior fabric in their compressed and deformed configuration. The thin sections will be returned to MSFC from UCB for postmission analyses and theoretical studies.

FIGURE 140.—Mission Specialist Carl Walz with MGM specimen during testing on STS–79.

The joint effort between UCB and MSFC will be reported in three postflight reports, scheduled for October 1996, March 1997 and September 1997, respectively.

The current plans for the subsequent two test series of the MGM experiment are now scheduled for STS–86 to take place in August 1997. In both test series, The specimens will be fully saturated with water and will be undrained during testing. In the first of these two test series the specimens will be subjected again in five compression-unloading cycles (fig. 139), whereas in the second series the loading will be cyclic, which will simulate earthquake loading. Figure 141 shows this type of loading.

Costes, N.C.; and Sture, S.: "The Potential of Soil Dynamics Research in Space." Proc. International Conference Recent Advances in Getechnical Eartquake Engineering and Soil Dynamics, St. Louis, Missouri, vol. 3, pp. 929–959, 1981.
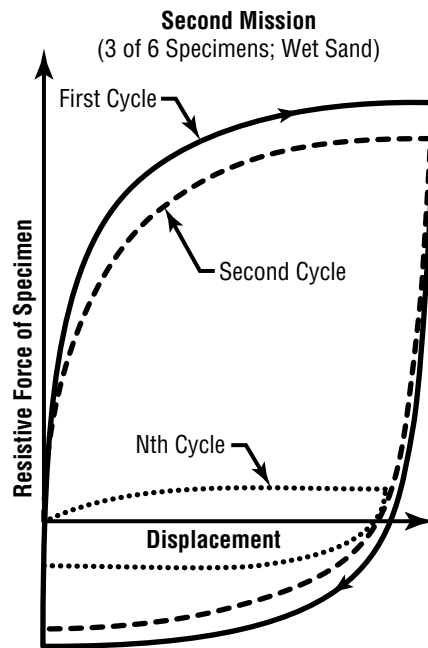
FIGURE 141.—Cyclic specimen loading sequence.

Costes, N.C.; Janoo, V.C.; Sture, S.: "Microgravity experiments on Granular Materials." Proc. Materials Research Society, vol. 87, pp. 203–212, 1987.

Costes, N.C.; Sture, S.; McTigue, D.F.: "Mechanics of Granular Materials at Very Low Effective Stress Levels." Proc. ASCE, 9th Engineering Mechanics Conference, pp. 1035–1038, 1992.

Peric, D.; Runesson, K.; Sture. S.: "Evaluation of Plastic Bifurcation for Plane Strain Versus Axisymmetry." ASCE, *Journal of Engineering Mechanics*, vol.118, no. 3, pp. 512–524, 1992.

Runesson, K.; Peric, D.; Sture, S.: "Effect of Pore Fluid Compressibility on Localization in Elastic-Plastic Porous Solids under Undrained Conditions." *International Journal of Solids Structures*, vol. 33, 1996.

Biographical Sketch: Dr. Nicholas Costes is a civil engineer in the Microgravity Science and Applications Division, Space Sciences Lab, specializing in fluid and geomechanics. He holds a Ph.D. in soil mechanics from North Carolina State University. He is the principal investigator on the Mechanics of Granular materials Microgravity experiment. Costes was a co-investigator on many Apollo mission lunar geology experiments and was a member of the Lunar Roving Vehicle design team. ◉